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Application of the Alternating Current Galvanometer to the Measurement of Capacity

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APPLICATION OF THE ALTERNATING CURRENT GALVANOMETER TO THE MEASUREMENT OF CAPACITY

BY

JAMES PERRY COYLE

A. B. Lake Forest College, 1910

THESIS

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

James Perry Coyle

ENTITLED Application of the Alternating Current Galvanometer to the Measurement of Capacity

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Arts in Physics

A. P. Carman E. H. Williams
In Charge of Major Work

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Recommendation concurred in:

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Final Examination

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INTRODUCTION

The measurement of capacities to a high degree of accuracy, especially those of small values, is attended with many difficulties. In the first place, the insulation must be very high so as to be sure that the quantity of electricity being measured is that from the capacity alone. Secondly, the inductance in all branches of the network must be reduced to zero. Furthermore, since the apparent capacity of condensers in which dielectrics of appreciable absorption coefficient are used, varies with the time of charge, voltage, etc., any expression for the value of the capacity of such a condenser becomes an indefinite quantity. It is, therefore, desirable to use dielectrics of very small or negligible absorption coefficients in order that the capacity of the condenser may be constant under varying conditions.

Of the two methods of measuring capacities, null and deflectional, the former usually gives the better results. The ordinary instrument used for detecting a balance when using alternating or intermittent currents in the null method is the telephone receiver. This has its limitations. In order to have its maximum sensibility, it should be adjusted to the frequency with which it is to be used. Even then there is usually a considerable range through which no change can be detected, and therefore the mean between two different values must necessarily be taken as the point of balance.

A vibration galvanometer may be used for detecting this balance point, but with such an instrument a highly constant source of alternating current giving a uniform frequency is necessary in order to obtain reliable results. To obtain such a constant source is always difficult, and in many laboratories impossible.

Resistances, potential differences, and current strengths can

be measured to a high degree of accuracy, and for many purposes it is desirable to measure capacities to the same degree of accuracy. At the same time it is desirable to have methods by which the work of measurement can be done with ease and rapidity.

It is the purpose of this investigation to compare the telephone receiver with the alternating current galvanometer as a means of obtaining a balance; and to make this comparison for various ranges of capacity; and finally to use the more sensitive detector in the determination of dielectric constants.

DESCRIPTION AND THEORY OF THE ALTERNATING CURRENT GALVANOMETER

Measurements of small capacities and inductances have recently assumed great importance on account of wireless telegraphy, and the alternating current galvanometer has been evolved in an effort to measure these values with the maximum accuracy. The direct current type seems to be open to criticism for tests involving change of current, such as induction experiments, etc. Ballistic galvanometers have been tried, with their sensibility greatly increased by the use of Ayrton and Perry's secohmmeter, in which an intermittent current is used. The general opinion seems to be that the best method for measuring effects due to current changes will involve the use of alternating currents. The mechanical construction of the indicating instrument seems to have been the main obstacle so far.

The first mention in the literature of the subject of the construction of such a piece of apparatus is made by Stroud and Oates[1], although the electro-dynamometer had been used before that time with

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[1] Philosophical Magazine, 6, p. 707, Dec., 1903.

alternating currents. Stroud and Oates used what was essentially an electrodynamometer with laminated iron cores. Their instrument might be described as a movable coil D'Arsonval galvanometer, in which the permanent magnet is replaced by an electromagnet with a laminated iron core, actuated by a 100 volt alternating current. The solid core inside the moving coil of the ordinary D'Arsonval galvanometer was, in their instrument, replaced by a laminated one. The great difficulty in manipulating such an instrument was due to the fact that a closed coil suspended in a magnetic field due to an alternating current takes up a position of great stability, such that its axis is at right angles to the field, or so that the coil itself will include a minimum number of lines of force. Since in any use of the instrument the circuit through the coil must necessarily be closed through a greater or less resistance, this stability decreases the sensibility enormously. Stroud and Oates overcame this difficulty by winding the coil on a broad copper frame, in which the Foucault currents induced in the sides acted like a closed coil placed at right angles to the galvanometer coil. This effect was made to predominate so that the coil when on open circuit took up a position so as to include a maximum number of lines of force, and was then brought back to zero by shunting with a suitable resistance. The chief objection to this method of control is that it necessarily limits the range for which the galvanometer is sensitive. For if the external circuit includes capacity, the leading current produced by this in the coil will have the same effect as the torque on the sides of the frame, necessitating so small a shunt resistance as to greatly reduce the sensibility as well as to cause an annoying drift in the zero reading. Thus, to retain the maximum sensibility when changing from the

measurement of small to that of large capacities involves the construction of a new coil wound on a different sized copper frame.

Figure 1 shows the effect of inductance and capacity on the movable coil. Let OD represent the magnetic flux of the field, then the

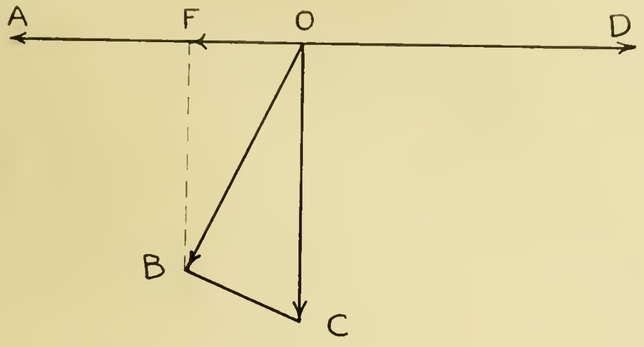

Fig. 1.

vector OC represents the current induced by it in the galvanometer coil, providing it had no inductance, but simply resistance. There would then be no force acting on the coil, for the product of two vectors at right angles is zero. Since, however, the coil possesses inductance, the current lags behind OC and may be represented by the vector OB. The component, OF, of this vector, being 180° behind OD, gives the repulsion which produces the undesirable stability. If a capacity be shunted across the coil sufficient to swing OB ahead until it reaches the position OC, then the condition of maximum sensibility has been reached. If, however, the capacity be still further increased, so that the current has a component in the direction OD, then there will be an attraction, and the coil will swing around so as to include a maximum number of lines of force.

Terry[1] has made use of this fact as a method of control, and

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[1] Physical Review, Vol. 21, p. 193, 1905.

thus evolved a simple and effective way of producing maximum sensibility. Instead of winding his coil on a copper frame as was done by Stroud and Oates, he wound it on a wooden frame, and depended entirely on resistance and capacity shunted across the coil to produce the maximum sensibility. If capacity predominated in the system with which he was working, the resistance shunted across the coil was decreased thus producing a greater lag in the current. On the other hand, if inductance predominated, and the lag was too great, that is, if the coil was too stable, capacity was shunted across the movable coil until the desired lead in the current was obtained.

Unless the suspensions are very heavy, they have in general but little to do with the initial position of the coil when the field current is flowing, since the induced currents in the coil react with the field in such a way as to produce a torque whose direction depends on whether the induced current leads or lags with respect to the induced electromotive force. Under ordinary conditions the magnitude of this torque is large compared with the restoring force of the suspension.

The galvanometer used in the following work was built in the shops of the Physics department of the University of Illinois, and is similar to the one described by Terry. It consists of 600 turns of number 16 double cotton-covered wire wound on a laminated core built up of sheets of transformer iron - C-shaped, with the movable coil of 600 turns of number 40 double cotton-covered copper wire hung in the opening. See Fig. 2.

III ACCESSORY APPARATUS

Mica condensers.- The standard mica condensers used in the arms of the Wheatstone Bridge were two Leeds and Northrup boxes, each

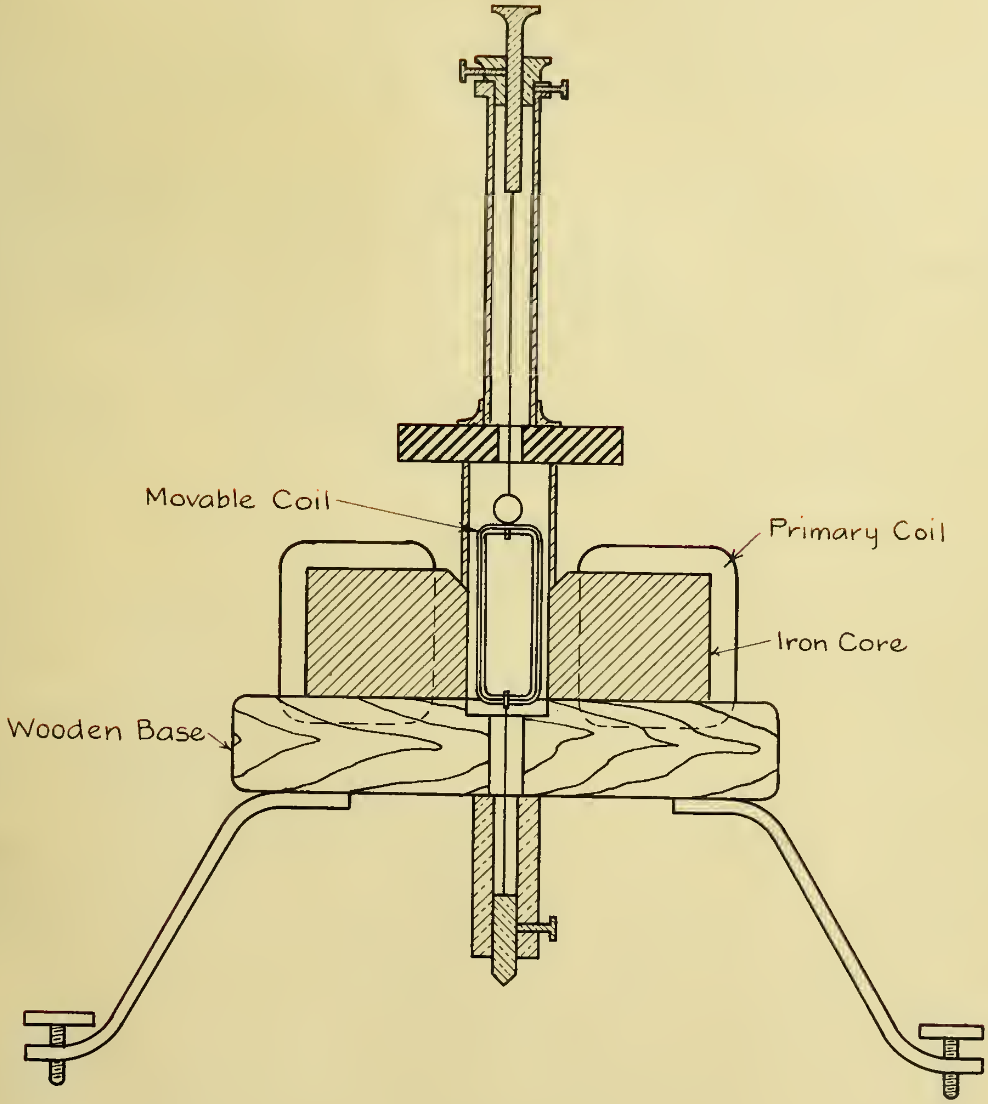

Fig. 2.

having six single capacities ranging from .05 to .5 microfarads, which, with the various combinations, series and parallel, gave a possible range from .0193 to 1 microfarad.

Air condensers.- During the course of the investigation two air condensers were constructed in the departmental shop. Of the various kinds of standard air condensers, spherical, parallel plate, and cylindrical, the parallel plate form was chosen as easiest in construction.

A brass condenser was constructed of eight parallel plates of sheet brass, - 38.2 x 30.4 x .12 cm., making seven condensers which were connected in parallel. These plates were 0.2 cm. apart, being held rigidly in place by six blocks of ebonite 1.3 x 2.3 x 5.6 cm., slotted to receive them, and insulated from each other by bits of ebonite .3 x .4 x .2 cm., placed between adjacent sheets at each corner and at the middle. Due to the fact that the brass plates were not uniformly plane, but tended to buckle, it was impossible to construct a uniform condenser whose actual capacity as experimentally determined would check closely with the theoretical capacity as computed by formula. However for the purpose in view, i.e., the determination of dielectric constants, this irregularity was not so important, as the dielectric constant is a ratio of capacities, and the discrepancy due to the lack of uniformity in distance between the plates would be constant in both determinations.

Sheet aluminum was found to be more nearly uniformly plane, and in a similar manner a standard parallel plate condenser was constructed of nine plates of sheet aluminum, 46.0 x 30.5 x .16 cm., with 2.0 mm. distance between plates, and insulated from each other as before.

From these measurements the capacities of these condensers could

be computed from the formula given by Gray[1]

$$C_1 = \frac{S}{4\pi d}$$

where C_1 is the capacity in electrostatic units. This formula becomes, for n plates in parallel,

$$C = \frac{(n-1)}{9 \times 10^5} \frac{k S}{4\pi d}$$

where C is the capacity in microfarads, k is the dielectric constant of the medium between the plates (for air this is very nearly unity and drops out of the equation), S is the area of each plate, and d the distance between plates.

No cognizance was taken in calculating the capacity of the condensers in this way, of the unequal distribution of electric force at the edges of the planes - a small correction for which can also be made by formula. This edge effect could be nullified by the use of a guard ring such as is described by Fleming[2].

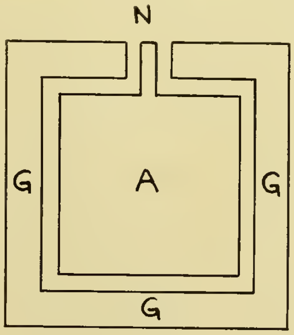

Fig. 3

According to this method two large pieces of plate glass are silvered. Upon one of them an area is delimited by scratching or removing the silver from the surface in a narrow band running round

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[1] A. Gray. - Absolute Measurements in Electricity and Magnetism p. 57.

[2] J. A. Fleming - Handbook for Electrical Laboratory and Testing Room, Vol. 2, p. 115.

the surface A, Fig. 3, but leaving a narrow neck N for the discharge. The two pieces of plate glass are then placed with silvered surfaces toward each other, and separated from each other by small pieces of glass whose thicknesses are uniform. In charging and discharging such a condenser, the charge on the guard ring G must be given and removed simultaneously with that of the area A, but by an independent circuit.

Such a condenser would be quite difficult and expensive to construct, and the silvered surfaces are not at all permanent. At the beginning of the investigation it was the intention to construct such an air condenser, but to use aluminum paint as a conductor instead of the silvered surfaces, it having been successfully used in making electrometer needles conducting. Plate glass, twenty-four inches square, was coated with aluminum paint, and a guard ring similar to that shown in Fig. 3 was insulated from the inner surface by removing a narrow strip of paint. It was found, however, that the material, varnish, used to hold the particles of aluminum together made the combination a non-conductor, or nearly so. For want of sufficient time in which to experiment with the various kinds of aluminum paints in order to see which kind, if any, would be sufficiently conducting for this purpose, the construction of this form of air condenser was abandoned. Such a condenser, however, is entirely possible to construct, provided that the proper kind of aluminum paint is secured. This has the advantage of being cheaper and easier of construction, also of being more permanent than the silvered surface suggested by Fleming.

RESISTANCES

The resistances used in the Wheatstone Bridge arrangement were

two Otto Wolff boxes with coils ranging from 0.1 to 10,000 ohms, which were accurate to 1/25 to 1/50 per cent. In measuring capacities of small value, however, these boxes would not be reliable when using alternating current, since the coils have an appreciable inductance, which will be spoken of later.

SOURCES OF CURRENT

During the preliminary work the commerical lighting circuit - 110 volts, and 60 cycles,-was used, it being supplied directly to the field coil of the galvanometer, which was shunted with three "tin rheostats", from which any desired potential of the same phase and frequency as that of the field coil could be taken off for the bridge current. In order to increase the sensibility of the balance, this latter potential was gradually increased during the course of the work until with the last measurements, the entire 110 volts were applied to the bridge. At first the commercial current seemed steady enough, but for the later more accurate determinations, it was found necessary to use a motor-generating set. The power for the direct-current motor of this machine was supplied from fifty-five storage cells, the generator giving off 110 volts alternating current, with a frequency of about 60 cycles. Whatever the frequency used, it could be kept practically constant, thus avoiding the annoyance caused by the shifting of the zero or balance point.

IV METHOD OF MEASUREMENTS

The method employed in making the measurements which are given on the following pages was the simple comparison method of DeSauty[1].

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[1] Fleming. Handbook for Electrical Laboratory and Testing Room, Vol. 2, pp. 145-146.

The two condensers, whose relative capacities C_1 and C_2 are to be determined, take the place of two arms of a Wheatstone bridge. (See Fig. 4). Two resistances R_1 and R_2, of minimum inductive effect form

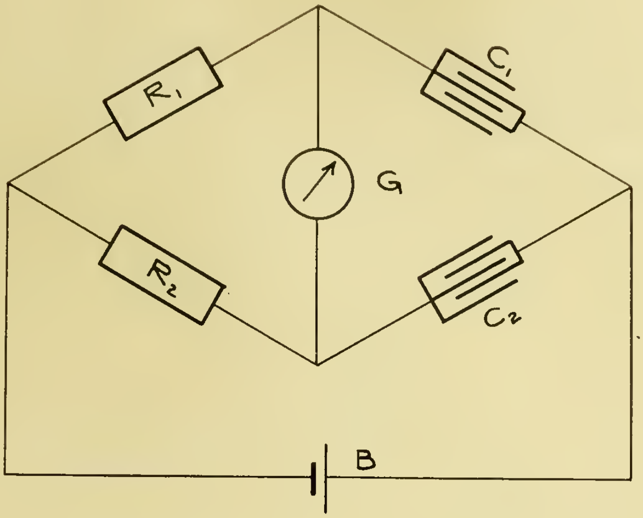

Fig. 4

the other two arms. In obtaining a balance these resistances are altered in value until the galvanometer in the bridge circuit gives no deflection on completing the battery circuit either when the condensers are charged or when they are charging or discharging. A complete discussion of the theory of this method is given in the Philosophical Magazine by Dr. R. T. Glazebrook[2].

Let v_0 (Fig. 4) be the potential of the common terminal of the condensers, and v that of both terminals of the galvanometer when balance is established. Let v_1 be the potential of the common terminal of the resistances. Then the quantities of electricity flowing through the resistances R_1 and R_2 during the small time dt will be $(v_1 - v)\frac{dt}{R_1}$ and $(v_1 - v)\frac{dt}{R_2}$ and the corresponding increase in the

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[1] Philosophical Magazine, May, 1881, p. 370.

potentials at the galvanometer terminals will be $(v_1 - v)\frac{dt}{C_1R_1}$ and $(v_1 - v)\frac{dt}{C_2R_2}$. These increases will be equal if the galvanometer continues to give no deflection; that is, the potentials at the points v must throughout the discharge be the same at each instant, for the condensers could not discharge in such a way as to give a current, first in one direction, and then in the other, through the galvanometer, and so keep the deflecting coil at rest. Therefore

$$(v_1 - v)\frac{dt}{C_1R_1} = (v_1 - v)\frac{dt}{C_2R_2}$$

whence

$$C_1R_1 = C_2R_2$$

and

$$C_1 = \frac{C_2R_2}{R_1}$$

It should be emphasized that this method is not applicable to the measurement of the capacity of a condenser with a dielectric having an appreciable coefficient of absorption.

The work of Anderson[1] should be noted here in connection with this theory. He measured capacities of a very small order, using the same set-up, but employing a telephone receiver to detect the point of balance. He used the 1000 ohm coils in two Hartman and Braun electrolytic bridges, wound according to the Chaperone principle, and giving a minimum capacity effect. Keeping the resistances constant, he balanced by adjusting a variable air condenser previously calibrated. S. L. Brown[2] has measured the residual capacity of a 1000 ohm Hartman and Braun coil, Chaperone wound, such as Anderson used, and found it to be .000105 mf. Assuming this result to be correct, Anderson arrives at the conclusion that the Wheatstone Bridge method cannot be used for measuring capacities of an order of .0005 mf. or less without

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[1] Physical Review, Vol. 34, January, 1912.

[2] Physical Review, Vol. 24, pp. 369-391.

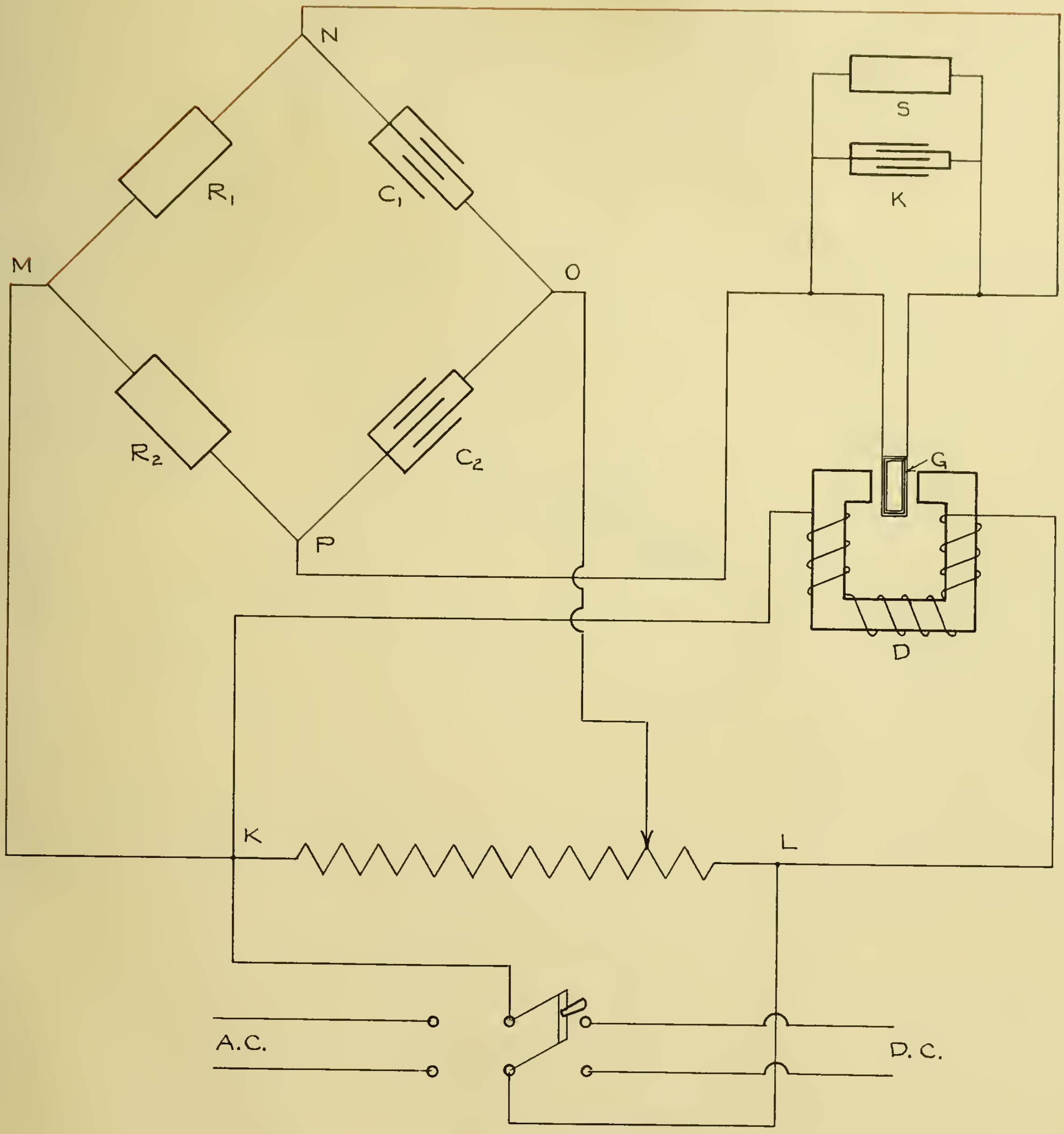

Fig. 5

having resistances wound to meet the conditions of the equation

$$\frac{R_2}{R_1} = \frac{C_1}{C_2} = \frac{c_1}{c_2} ,$$

c_1 and c_2 being the respective capacities of the resistances R_1 and R_2. This formula is developed mathematically in his article. The above criticism, however, does not apply to the present work as all the capacities measured were of a higher order of magnitude than .0005 microfarads.

Figure 5 shows a complete diagram of the set-up. The alternating current is brought in at A, and sent in to the field coil, D, of the galvanometer. Shunted across the main circuit are the three tin resistances, KL, from which any drop of potential desirable can be picked off and sent through the bridge circuit at the ends of the diagonal MO. The movable coil of the galvanometer is connected to the points N and P on the bridge. Shunted across G are a resistance, S, and a capacity, K, used jointly as the control circuit of the galvanometer according to the method discussed earlier in this work.

V COMPARISON OF THE RELATIVE SENSIBILITIES OF THE TELEPHONE RECEIVER AND THE ALTERNATING CURRENT GALVANOMETER FOR DETECTING ALTERNATING CURRENT BALANCES

The data in Tables I to V were taken to show the relative sensibility of the alternating current galvanometer and the telephone receiver in detecting the balance point in the Wheatstone bridge set-up. In each of these tables, three balance points were taken with the alternating current galvanometer, and three with the telephone receiver. C_2 was taken as given on the standard capacity box, or as previously determined. The balances were obtained by varying R_2.

TABLE I

Galvanometer

R_1	R_2	C_1	C_2
19900	13625	.00349005	.0050974
19700	13490	.00349055	.0050974
19500	13355	.00349107	.0050974

Receiver

19500	13500	.00352897	.0050974
19700	13700	.00354489	.0050974
19900	13800	.00353483	.0050974

TABLE II

Galvanometer

18500	18375.3	.0248315	.025
19500	19368.5	.0248314	.025
19900	19765.7	.0248313	.025

Receiver

18400	18295	.0248573	.025
19100	19000	.0248691	.025
19650	19525	.0248407	.025

TABLE III

Galvanometer

19000	18874.3	.0993384	.1
19900	19768.85	.0993410	.1
19400	19272.15	.0993410	.1

Receiver

18900	18800	.0994709	.1
19900	19800	.0994975	.1
19200	19090	.0994271	.1

TABLE IV

R_1	R_2	C_1	C_2
		Galvanometer	
19000	19033	.500868	.5
18500	18532	.500865	.5
19900	19940	.501005	.5
		Receiver	
18850	18900	.501326	.5
18350	18400	.501362	.5
18770	18825	.501465	.5

TABLE V

		Galvanometer	
19200	19347	1.00765	1.
19520	19673	1.00784	1.
19820	19985	1.00832	1.
		Receiver	
18620	18690	1.00376	1.
17630	17700	1.00397	1.
15600	15655	1.00353	1.

From an examination of the above data, it would seem at a glance that the telephone receiver is almost as good as the galvanometer in detecting a balance point, since the various sets of readings agree among each other so closely, but the values for R_2 for the receiver in each case are the means of two resistances from fifty to one hundred ohms apart, through which no apparent change in the balance point could be detected. The values for R_2 in the case of the galvanometer, on the other hand, are the means of two resistances from 0.2 to 1.0 ohm apart, except in the case of one set of readings, since a change

of that degree could be detected. Under the conditions with which the above data were taken, the sensibility of the alternating current galvanometer seemed to depend on the size of the capacity to be measured. Thus in Tables II and III the sensibility was .2 ohm in 20,000 ohms or .001 per cent, - a value far beyond the accuracy of the resistance boxes. For both higher and lower values the sensibility decreased, being only 5 ohms in 20,000 when the capacity was one microfarad. This is a sensibility of .025 percent, which is still equal to or greater than the accuracy of the resistance boxes. The sensibilities for the various capacities experimented with are given in Table VI. In each case the resistance which was being varied was about 20,000 ohms.

TABLE VI

Capacity	Galvanometer sensibility
.0035 M.F.	1. ohm
.025	.2
.1	.2
.5	.5
1.0	5.0

VI DETERMINATION OF CAPACITIES OF THE AIR CONDENSERS

Tables VII and VIII give the data obtained in the determination of the capacities C_1 of the two air condensers. In each case a standard mica condenser was used for C_2.

TABLE VII

Brass Condenser

R_1	R_2	C_1	C_2
19977	3618.5	.003477	.01923
19977	2783.2	.003483	.025

TABLE VII continued

R_1	R_2	C_1	C_2
19900	3603.75	.003482	.01923
14900	2698.45	.003483	.01923
14900	2074.2	.003480	.025

TABLE VIII

Aluminum Condenser

19900	5273.5	.0050960	.01923
19500	5171.6	.0050999	.01923
19000	5039.7	.0051009	.01923
15000	3978.55	.0051005	.01923
19900	4056.0	.0050955	.025
19500	3974.0	.0050949	.025
19000	3871.35	.0050939	.025

TABLE IX

Brass Condenser Compared With Aluminum Condenser as Standard

19700	13555	.00350747	.0050974
19500	13418	.00350917	.0050974
19300	13280	.00350743	.0050974
19000	13073	.00350728	.0050974

In Table IX, the aluminum condenser was compared with the brass condenser. The aluminum condenser was taken as the standard, and its value was taken as the mean of the values given in Table VIII.

The results found for the value of the capacity of the brass condenser in this case differ by about one percent from those found in Table VII. It is difficult to account for this discrepancy unless it be true that the resistances have an appreciable amount of

self-inductance, or that in one of the sets of readings a connecting wire became looped in such a way as to insert some extra inductance. It will be noticed that in Table VII, R_2 is below 3000 ohms in every case, whereas in Table IX it is about 13000 ohms.

Since, in the later work, the brass condenser was to be used in a metal pan it was decided to see what effect, if any, the presence of the pan would have on its capacity. After carefully insulating the condenser from the pan, as well as the pan from the pier on which it rested, by means of hard rubber blocks, the capacity was again compared with the aluminum condenser. The results of this comparison are shown in Table X. The mean of the values of C_1, 0.00348309 microfarads, obtained in these measurements, was taken as the value of the capacity of the brass condenser with air as a dielectric. This value is approximately the same as that found for the same condenser in Table VII.

TABLE X

Brass Condenser Compared with Aluminum Condenser as Standard, with Former in Iron Pan

R_1	R_2	C_1	C_2
19500	13331.5	.00348487	.0050974
18000	12302.5	.00348392	.0050974
18000	12301	.00348351	.0050974
18500	12641	.00348304	.0050974
18800	12846	.00348304	.0050974
19000	12983	.00348313	.0050974
19200	13119	.00348296	.0050974
19900	13597	.00348289	.0050974

VII DETERMINATION OF THE DIELECTRIC CONSTANT OF KEROSENE

The dielectric constant of the substance between the plates of a condenser is one of the factors in determining its capacity. The dependence of the capacity on the dielectric constant is given by the formula

$$C = \frac{K\ A}{4\pi d}$$

where K is the dielectric constant, A the effective area of the plates and d the distance between the plates. Thus it is seen that the capacity is directly proportional to the dielectric constant. Hence if the capacities of a condenser are measured with two different media between its plates, for one of which the dielectric constant is known, a means is furnished whereby the dielectric constant of the other may be calculated. Furthermore, since the alternating current galvanometer furnishes a very sensitive means of obtaining a balance, it is evident that any slight change in the dielectric constant of a substance due to temperature change can be easily detected.

Tests were made for kerosene in which its dielectric constant was determined according to the above method and its temperature coefficient determined over a small range of temperature. Table XI gives the results.

TABLE XI

Brass Condenser with Kerosene at 30°C as Dielectric

R_1	R_2	C_1	C_2	K
13900	19730	.00723537	.0050974	2.077285
14050	19943	.00723541	.0050974	2.077397
13700	19448	.00723608	.0050974	2.077489
13500	19161	.00723491	.0050974	2.077153
13300	18881	.00723639	.0050974	2.077578
13100	18599	.00723714	.0050974	2.07793

TABLE XII

Brass Condenser with Kerosene at 29.5°C as Dielectric

R_1	R_2	C_1	C_2	K
13400	19060	.00725048	.0050974	2.08162
13600	19342	.00724955	.0050974	2.08136
13800	19628	.00724955	.0050974	2.08136

TABLE XIII

Brass Condenser with Kerosene at 10.5°C as Dielectric

13800	19850	.00733239	.0050974	2.10514
13600	19551	.00732022	.0050974	2.10164
13400	19260	.00732656	.0050974	2.10347

obtained when the brass condenser was immersed in kerosene at a temperature of 30°C. Table XII is data taken for the same condenser at a temperature of 29.5°C and table XIII gives the results when the temperature was 10.5°C. Great difficulty was experienced in maintaining the temperature constant at 10.5° with the temporary arrangement which was at hand. However, the change in dielectric constant when the temperature is changed from 30°C to 10.5°C is easily measured, it varying from 2.077472 at 30°C to 2.1034 at 10.5°C.

VIII CONCLUSIONS

According to the results obtained in this investigation, it is evident that the alternating current galvanometer is very much superior to the telephone receiver as a sensitive means of detecting a point of balance in null methods involving the use of intermittent or alternating currents. Furthermore, these results indicate that the limit of accuracy with which capacities may be measured by comparison is determined by the accuracy of the standard capacity and resistances

used and the freedom of the latter from inductance and distributed capacity.

In conclusion the author wishes to express his appreciation to Professor A. P. Carman for the use of the laboratory facilities, and to Dr. E. H. Williams for his many suggestions.

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